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ABSTRACT

A method has been developed to predict the lift and thrust of an ejector wing by iterating between a viscous solution for the turbulent entrainment of the primary jets, and an inviscid solution for the ejector wing flow field. A two-dimensional analysis, which utilizes a turbulent kinetic energy model for the jet mixing calculation and a higher order panel method for the inviscid flow calculation, is described. The complete ejector wing geometry is analyzed. Detailed surface pressures both inside and outside the ejector can be calculated. A sample calculation for a typical ejector wing configuration is compared to experimental data.

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INTRODUCTION

Although analytic methods are necessary for conceptual studies and to reduce test requirements, there is no satisfactory theory for predicting ejector wing performance. Methods have been developed to calculate the surface pressure distributions induced by an ejector of given thrust. These calculations are based on the now classical vortex sheet model of the pure jet flap devised by Spence (ref. 1). Linearized, thin airfoil models of the ejector wing were developed by Chan (ref. 2) and Woolard (ref. 3), who added a sink on the upper surface of a jet-flapped wing to represent the entrainment into the ejector. Wilson (ref. 4) extended this approach by including the effects of thickness and camber, as well as deflection of the jet wake. More recently, Dillenius and Mendenhall (ref. 5) studied three-dimensional effects. In all these methods, experimental data are used to specify the variation in ejector thrust during conversion from hover to conventional flight.

Such an empirical approach is useful for estimating pressure distributions or for performing parametric analysis. However, a theory for predicting both the thrust augmentation ratio and the initial thrust angle is necessary to evaluate significant design changes, or new configurations for which there is no data base. Bevilaqua and DeJoode (ref. 6) developed a method for predicting the thrust augmentation of stationary ejectors by iterating between a viscous solution for the entrainment of the primary jets and an inviscid solution for the pressures induced on the ejector duct by the entrained flow. The purpose of this paper is to describe an extension of this analysis developed to predict the lift and thrust of the more complex ejector wing in transition flight.

Calculation of the flow field is more difficult in this case because deflection of the exhaust jet by the free stream influences both the thrust of the ejector and the lift of the wing. A two-dimensional analysis, which utilizes a turbulence kinetic energy model for the jet mixing calculation and a higher order panel method for calculating the surface pressures, has been developed.

A description of this analysis, together with a computed result is given in the following sections.

MATHEMATICAL MODEL

The interactions between the ejector and wing flow fields are computed without solving the full Navier-Stokes equations by iterating between a viscous solution for the flow through the ejector and an inviscid solution for the flow around the wing. Because the primary direction of flow is through the ejector, the governing elliptic equations can be reduced to a parabolic set which can be solved by marching through the ejector in the streamwise direction. The mixing

of the turbulent jets can then be used to define an equivalent sink distribution. The requirement that the ejector wing and jet boundaries must be streamlines of the flow together with appropriate jet dynamic boundary conditions determines the strength of the wing circulation. The circulation and jet shapes, in turn, control the entrainment calculated in the next iteration for the viscous solution.

Potential-Flow Calculation

The geometry of the two-dimensional ejector wing considered in this study is shown in Figure 1. It has three main components: a plain flapped wing, a central nozzle, and an aft flap. Primary jets are injected at the knee of the forward flap, the trailing edge of the central nozzle, and near the leading edge of the aft flap. The three jets grow and merge to define the jet wake, which has higher total pressure than the free stream does. Consequently, the flow consists of two regions with different total pressure, thus it is inhomogeneous

According to Kuchemann and Weber (ref. 7), the inhomogeneous flow may be made homogeneous without changing the flow velocity field by subtracting the total pressure difference between the jet wake and the main stream from the static pressure inside the jet wake. In the resulting homogeneous flow, the jet boundaries are unknown and to be determined as part of solution subjected to the usual tangential flow (kinematic) condition and an additional dynamic boundary condition

$$\Delta H = \rho U \gamma \tag{1}$$

where ρ is the fluid density (both jet and main stream), U is the mean velocity of the jet boundary, γ is the velocity difference across the jet boundary, and ΔH is the total pressure difference between the main stream and jet wake.

However, if the jets are not completely mixed by the ejector exit, each jet before complete mixing is treated as a thin jet using the classical thin jet theory. According to Spence (ref. 1), the static pressure jump, Δp, across a thin jet is balanced by the rate of change of jet momentum, J, due to jet curvature, 1/R, and is related to the vortex strength, γ, (equivalent to the velocity difference across the jet) of the jet sheet as follows:

$$\Delta p = \rho U \gamma = \frac{J}{R} \tag{2}$$

The solution of a thin jet is obtained by satisfying this dynamic boundary condition together with its kinematic boundary condition. All the flow singularities which determine the potential-flow solution are shown in Figure 1. The cross line source is added to combine with the line sink to simulate the doublet effects on the flow field for modeling

the effect of the jet, which acts like an elongated actuator disk to draw air through the ejector.

The potential flow just described is calculated by using the Hess (ref. 8) higher-order panel method. Both airfoil and jet boundaries are defined by a series of discrete points, so-called corner points, as shown in Figure 2. Between two successive corner points, the true geometry is approximated by a curved parabolic panel. A linear vortex distribution and a linear source distribution are placed on each of these panels. Source singularity strengths are chosen a priori and set equal to twice the local jet entrainment velocity. Vortex singularity strengths and the jet shapes are determined by satisfying the airfoil and jet kinematic boundary conditions and the jet dynamic boundary conditions, equations (1) and (2).

Since the jet dynamic boundary conditions, equations (1) and (2), are nonlinear and the jet shapes are not known, a priori, an iterative procedure shown in Figure 3 is adopted to obtain the potential-flow solution. Details of the computational procedure are given in ref. 9.

Jet-Mixing Calculation

The jet-mixing calculation is a partially parabolic method described in detail in ref. 10. The flow governing equations are derived from Reynolds' equations for turbulent flows, by neglecting streamwise diffusion and including curvature effects. A TKE turbulent model (ref. 11) modified to include the curvature effect is used to determine the turbulent viscosity. A set of finite-difference equations are formed by integrating the governing differential equations over a small control volume. The resulting finite difference equations are solved iteratively for velocity and pressure fields. Briefly, the iterative procedure begins with an initial guess of the pressure field, solves the momentum equations for the velocity components using a triadiagonal matrix algorithm, corrects the pressure and velocity fields to satisfy the continuity equation, and repeats the process until convergence is obtained.

SOLUTION MATCHING PROCEDURE

The solution is iterative, since the two individual flow problems and their coupling are nonlinear. The iterative procedure used is summarized schematically by the flow chart of Figure 4. Details of the computational procedure are described in ref. 9. Presently, the potential-flow program and the jet-mixing program are separated and communicate through external data transformation.

EXAMPLE SOLUTION

To test the present matching solution procedure for ejector wings, the model wing "Configuration Augmenter 1" (Figure 7) of ref. 12 was analyzed at a transition operating condition. The tunnel velocity was 34.4 m/sec (113 ft/sec) for a tunnel static pressure of 1.024 atmospheres. The effective angle of attack was 2 degrees and the momentum coefficient was 2. Figures 8 through 12 show the calculated results and Stewart's (ref. 12) experimental data.

Comparison of the distributions reveals that the differences between the experimental and theoretical pressure are dramatically reduced when jet entrainment effects are included in the calculations. Examination of the experimental data shows large discrepancies near the leading edge and on the upper surface of the centerbody. These are most likely due to flow separation in these regions. The flow separation may be due to the high local angle of attack as indicated by the calculated flow streamline pattern about the ejector wing shown in Figure 12. The present computer program cannot calculate a separated flow.

CONCLUSIONS

1. A viscid/inviscid interaction analysis has been developed to predict the thrust augmentation ratio and initial thrust angle of ejector wing configurations. This provides an advance over classical methods of analysis, which require these parameters to be specified as an input.

2. Comparison of the predicted surface pressure distributions with experimental data establishes confidence in the model of the flow field. But in addition, a greater understanding of the performance of ejector wings has been obtained from the analysis.

3. Examination of the computed streamlines and surface pressures reveals the somewhat surprising result that the forward stagnation point is located near the trailing edge of the forward flap. This is a result of the large circulation induced by the jet flap effect and suggests that a leading edge device may be required to achieve maximum lift and thrust. Further, the surface pressure distributions on the other two elements suggest that the flow is more likely to separate from the central nozzle than the aft flap. Since the flow into the ejector is being accelerated past the nozzle, this was also an unexpected result.

4. The present analysis can be improved by including boundary-layer and three-dimensional effects.

5. It would be useful to have test data for a two-dimensional configuration, since no comparison with available three-dimensional data can be exact.

REFERENCES

1. Spence, D. A.: The Lift Coefficient of a Thin, Jet-Flapped Wing, Royal Society of London, Proceedings, vol. 238, January 1957, pp. 46-68.
2. Chan, Y. Y.: Lift Induced by Suction Flaps on Augmenter Wings, Canadian Aeronautics and Space Institute Transactions, vol. 3, no. 2, Sept. 1970, p. 107.
3. Woolard, H. W.: Thin-Airfoil Theory of an Ejector-Flapped Wing Section, AIAA Journal of Aircraft, vol. 12, no. 1, January 1975, p. 26.
4. Wilson, J.: Thrust Augmented Wing Section in Potential Flow, PhD Dissertation, West Virginia University, 1973.
5. Dillenius, M. F. and Mendenhall, M. R.: Theoretical Analysis of an Augmenter Wing for a VTOL Fighter, NASA CR-152254.
6. Bevilaqua, P. M. and DeJoode, A. D.: Viscid/Inviscid Interaction Analysis of Thrust Augmenting Ejectors, Report ONR-CR212-249-1, February 1978.
7. Kuchemann, D. and Weber J.: Aerodynamics of Propulsion, McGraw-Hill, Chapter 3, New York, 1953.
8. Hess, J. L.: Higher-Order Numerical Solution of the Integral Equations for the Two-Dimensional Neumann Problem, Computational Methods in Applied Mechanics and Engineering, vol. 2, no. 1, February 1973.
9. Bevilaqua, P. M.; Woan, C. J.; and Schum, E. F.: Viscid/Inviscid Interaction Analysis of Ejector Wings, NASA CR 166172, in review, 1981.
10. Schum, E. F.; Bevilaqua, P. M.,; and Patankar, S. V.: Computation of the Turbulent Mixing in Curved Ejectors, ONR-CR212-249-2F, April 1980.
11. Launder, B. E. and Spalding, D. B.: Mathematical Models of Turbulence, Academic Press, 1972.
12. Stewart, V. R.: A Study of a VTOL Thrusting Ejector in Low Speed Flight, vol. 1 and 2, NASA CR-166137, March 1981.

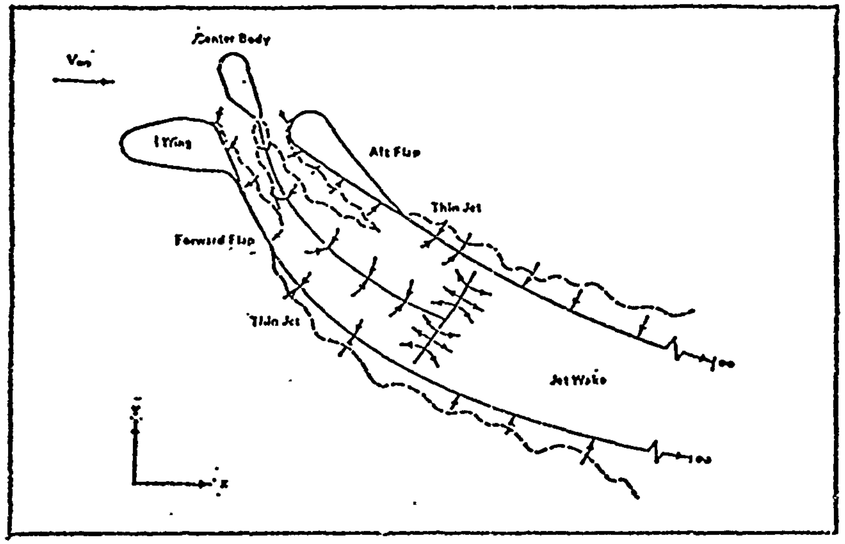

Figure 1 Mathematical Model of the Generalized Ejector Wing

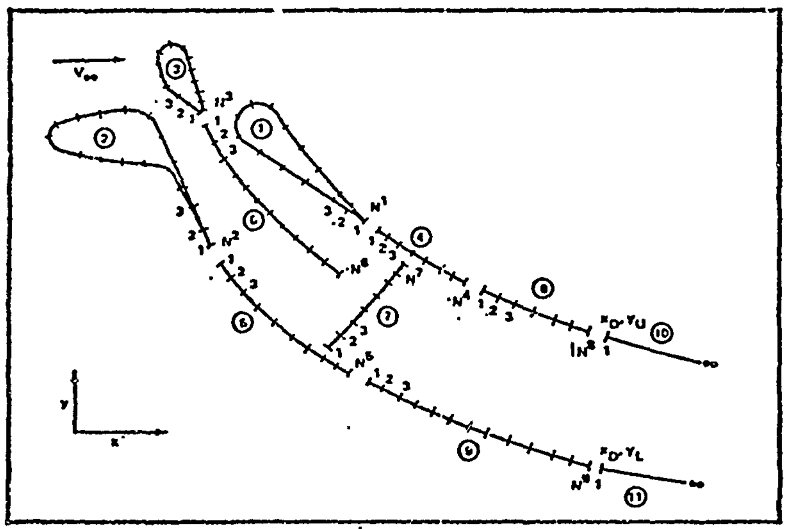

Figure 2. Isolated Elements and Direction of Indexing the Corner Points

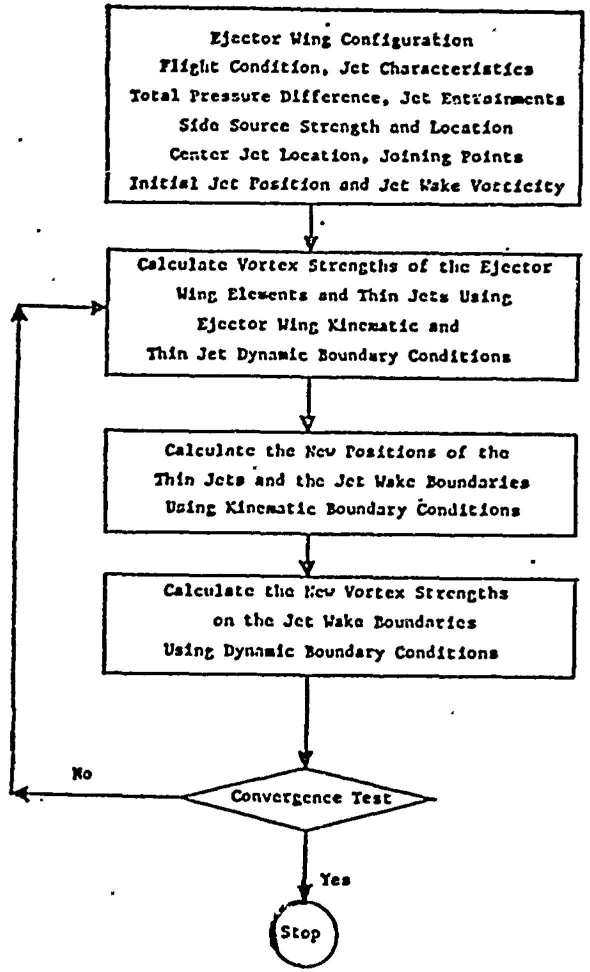

Figure 3. Inviscid Numerical Procedure

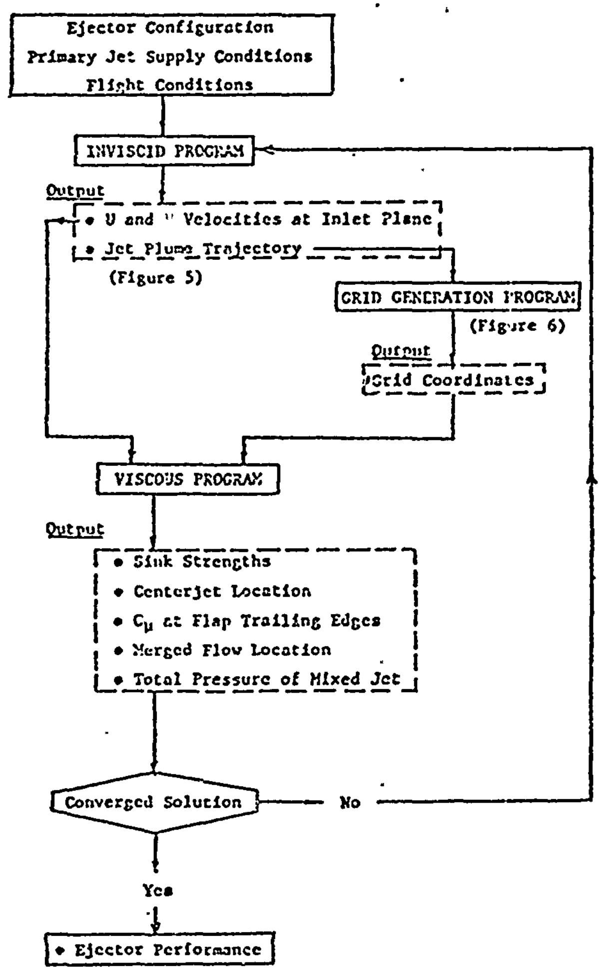

Figure 4. Inviscid/Viscid Matching Procedure

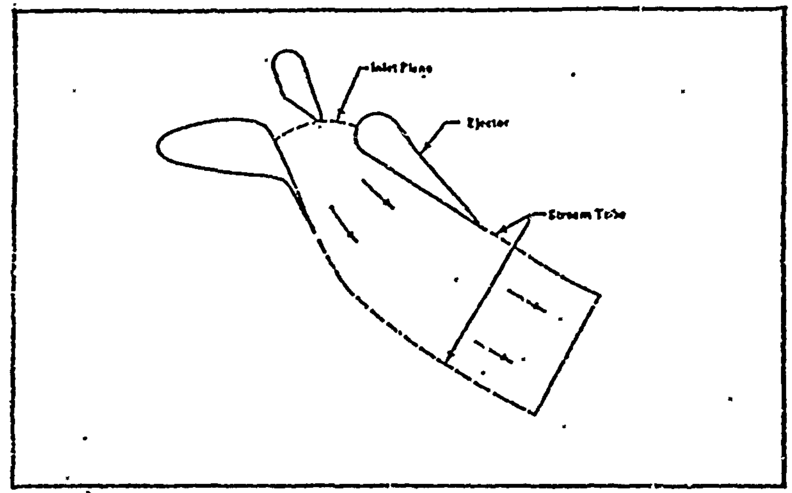

Figure 5. Flow Field Boundaries

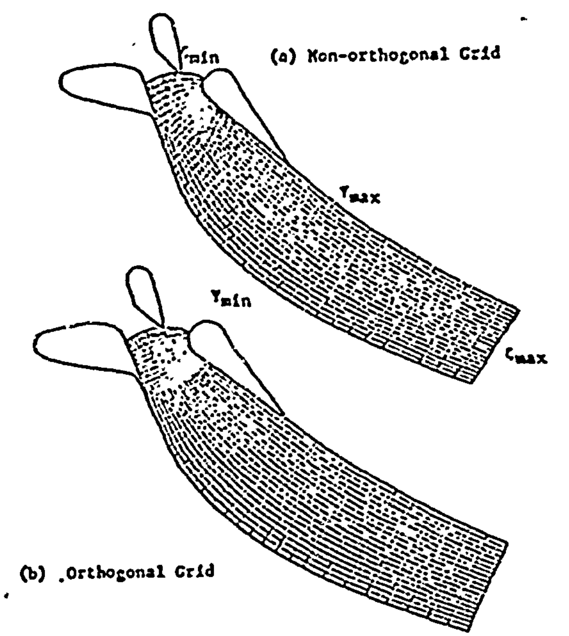

Figure 6. Boundary-Oriented Grids

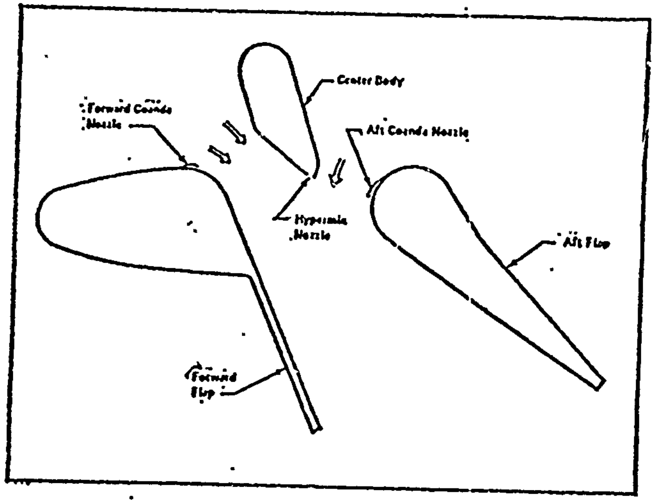

Figure 7. Experimental Model Configuration

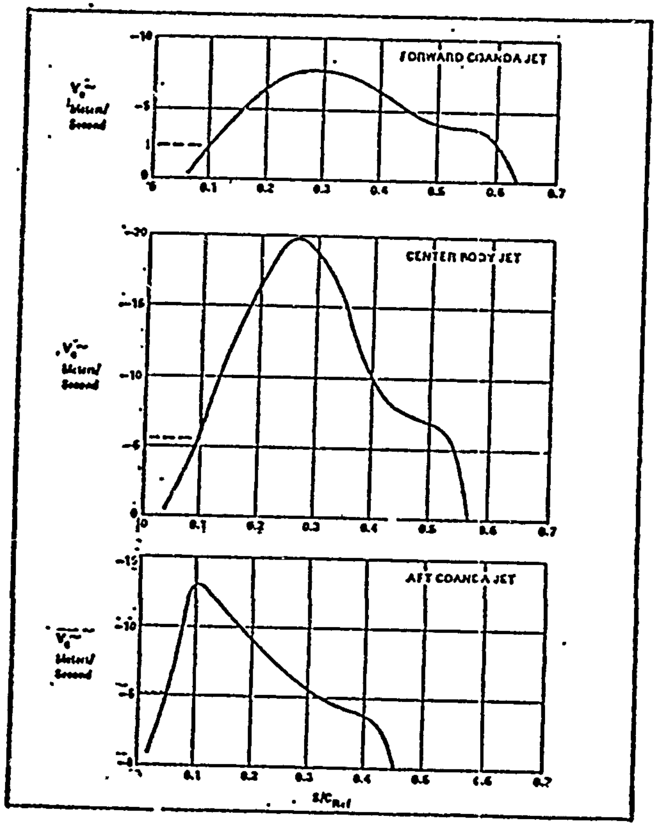

Figure 8. Sink Strengths

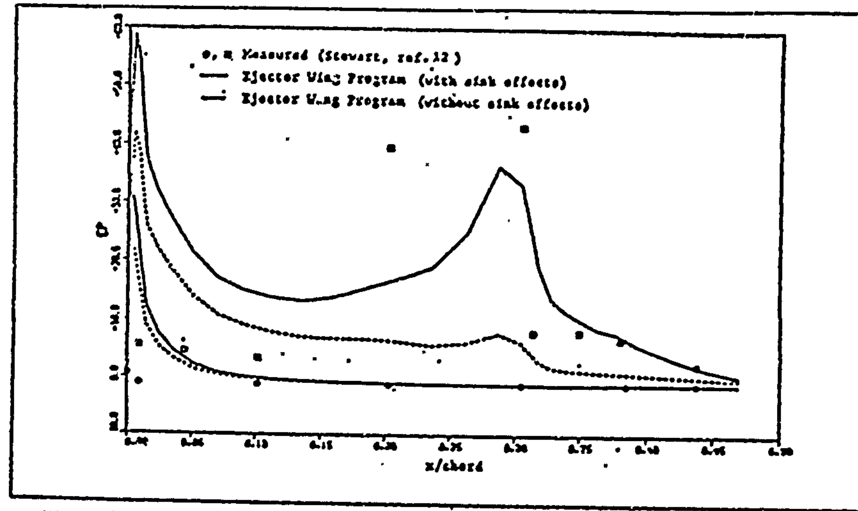

Figure 9. Comparison of the Calculated Pressure Coefficients with the Experimental Data for the Forward Flap.

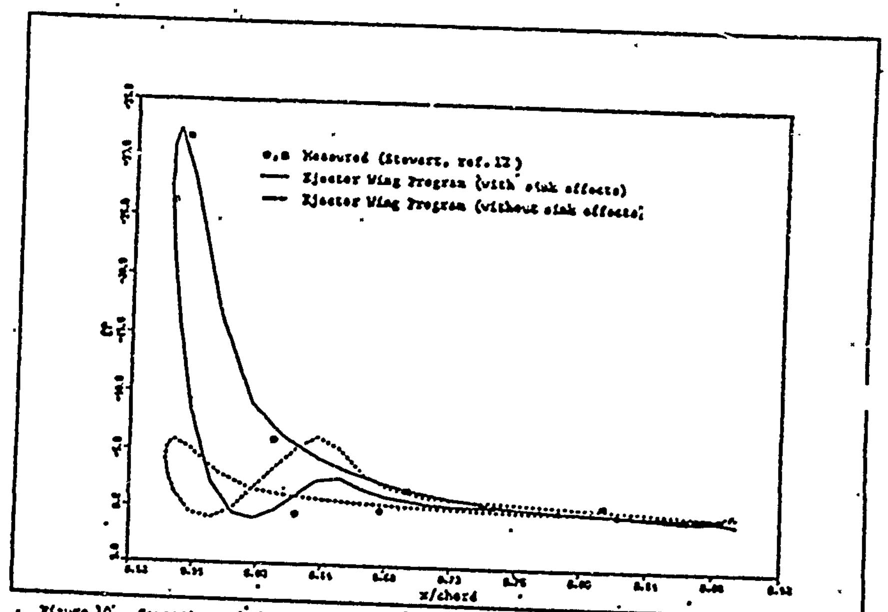

Figure 10. Comparison of the Calculated Pressure Coefficients with Experimental Data for the Aft Flap of the Ejector Wing

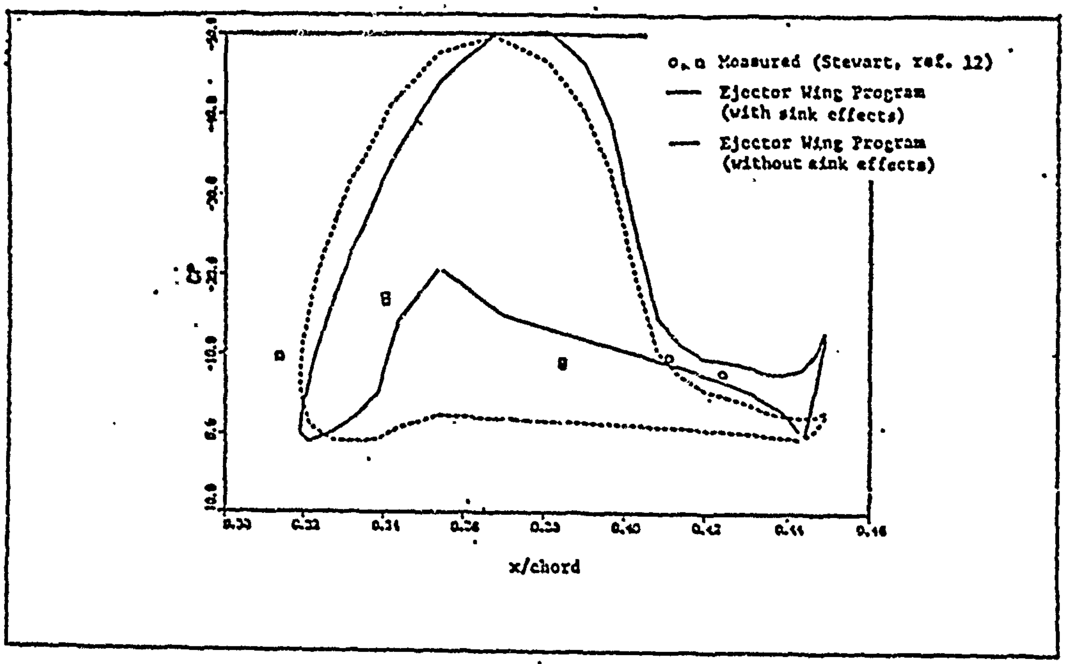

Figure 11. Comparison of the Calculated Pressure Coefficients with the Experimental Data for the Centerbody

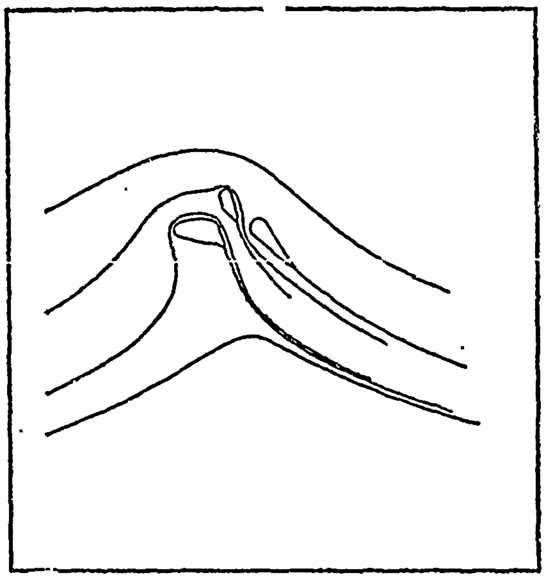

Figure 12. Calculated Flow Streamline Pattern about the Ejector Wing